

# PATENT SPECIFICATION

(11)

1 470 036

1 470 036

- (21) Application No. 2173/75 (22) Filed 17 Jan. 1975  
 (44) Complete Specification published 14 April 1977  
 (51) INT. CL.<sup>2</sup> G10K 11/02  
 B32B 3/12  
 (52) Index at acceptance  
 G5X 50  
 B5N 0312  
 H3U 24 25 26Y M  
 (72) Inventor LESLIE SPENCER WIRT

(19)



## (54) DUAL RANGE SOUND ABSORBER

(71) We, LOCKHEED AIRCRAFT CORPORATION a Corporation organised and existing under the laws of the State of California United States of America, of P.O. Box 551, Burbank, California 91520, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The present invention relates to sound absorption apparatus, and particularly a dual range sound absorber.

Although industrial noise pollution has existed for many years, it has become more acute through the use of higher speed machinery to increase production output. Also, modern jet engines — as is well known — produce a higher perceived noise level than the reciprocating internal combustion engines which they replaced. Surface vehicles have also contributed heavily to the problems of noise pollution.

One of the commonly used types of airborne-sound-absorption panel, of the prior art, comprises a sound permeable facing sheet, an interposed honeycomb core, and an impermeable backing sheet. Such devices are generally called "laminar absorbers". Although such panels are simple, strong, and lightweight, they have the disadvantage of being able to absorb sound only at certain discrete frequencies. Between these discrete absorption bands the absorption falls to a very low value. In many applications it is necessary to absorb both high-frequency and low-frequency sounds.

Perhaps the most difficult sound absorber design problem is to provide broadband low frequency sound absorption within a very restricted volume. Broadband sound absorbing materials of all types are subject to a fundamental space-versus-

frequency limitation. This arises because such materials are incapable of absorbing sound efficiently unless they are of the order of one-quarter wavelength in thickness. As the frequency to be absorbed becomes lower, the physical size of the absorber increases, and, in many cases becomes unacceptably large.

Heretofore it has been proposed to minimize the amount of absorbing material required for a sound absorbing system by placing a small amount of absorbing material in the throat of a horn. However, such devices do not provide the degree of reduction of physical volume afforded by the present invention.

Accordingly the present invention provides an apparatus for the absorption of wide frequency range ambient sound field, comprising means defining a sound-confining chamber and, an acoustical horn having a predetermined cut-off frequency and having a sound-receiving mouth at one end and a smaller throat at the other end of the horn path, said path being characterized by a continuously changing cross-sectional area along its length, said horn being nested within said chamber so as to have said mouth acoustically coupled to the exterior of said chamber and said throat acoustically coupled to the interior of said chamber, the internal volume defined by said chamber and said horn comprising a damped Helmholtz resonator, whereby incoming sound above said cut-off frequency will be propagated from said mouth towards said throat whereupon said sound will be reflected back toward said mouth due to the discontinuity at the junction of said throat and said chamber, thereby causing destructive interference between incoming and reflected sound waves, and whereby the inertia of the air mass in said horn resulting from incoming sound below said cut-off frequency is just

compensated by the air confined in said chamber so as to cause Helmholtz resonance to occur within said chamber.

According to a further aspect the invention provides a wide-frequency range sound absorber, comprising a parallel array of tuned Helmholtz resonator compartments and, a plurality of acoustical horns each having a predetermined cut-off frequency and a sound-receiving mouth at one end and a smaller open throat at the other end of the horn path, each of said horns being nested within corresponding compartments so as to have the mouths thereof acoustically coupled to the exterior of said array and the throats thereof acoustically coupled to the interior of corresponding compartments, said horns being characterized by a continuously-diminishing cross-sectional area between said mouths and said throats, whereby incoming sound above said cut-off frequency will be propagated from said mouths towards said throats whereupon said sound will be reflected back toward said mouths due to the discontinuity of the junctions of said throats and said compartments, thereby causing destructive interference between incoming and reflected sound waves, and whereby the inertia of the air masses in said horns, resulting from incoming sound below said cut-off frequency, is just compensated by the air confined in said compartments so as to cause Helmholtz resonance to occur within said compartments.

According to yet a further aspect the invention provides a wide-frequency range sound absorber comprising first and second sound-confining resonator compartments disposed in side-by-side relationship, said compartments having adjacent open ends, a first acoustical horn having a sound-receiving mouth at one end and a smaller open throat at the other end of the horn path, said path being characterized by a continuously changing cross-sectional area along its length, said horn being nested within said first compartment and having its throat in communication with the interior thereof, a second acoustical horn nested within said second compartment and having its throat in communication with the interior thereof, the cut-off frequency of said first horn being dissimilar to the cut-off frequency of said second horn and, a permeable flow-resistive element extending across the mouths of said first and second horns whereby the combination of said first horn and said first compartment is responsive to absorb a first distributed portion of the sound spectrum and the combination of said second horn and said second compartment is responsive to absorb a complementary distributed portion

of the sound spectrum.

A preferred embodiment of the invention disclosed herein comprises a relatively short horn-shaped passage nested in a closed cavity. The mouth of the horn is substantially contiguous with an exterior wall of the cavity and is covered by a flow resistive permeable sheet. The throat end of the horn communicates with the air space within the cavity. Below the design cut-off frequency of the horn, the air in the entire horn moves together and exhibits thereby a very considerable inertia. At some frequency below cut-off, the inertia of the air in the horn is just compensated by the stiffness of the air in the cavity and a resonance occurs. The resonance is heavily damped due to the presence of the permeable, resistive, facing sheet across the mouth of the horn. Above the cut-off frequency, the horn propagates incoming acoustic waves but the discontinuity in area at the junction of the throat and the air cavity causes a reflection to occur, thereby causing the system to function in a manner similar to a conventional laminar absorber. Thus, the damped resonance mechanism absorbs low frequencies while the laminar absorber mechanism absorbs higher frequencies. By proper selection of the horn, facing, and cavity parameters, the low frequency absorption zone and the high frequency absorption zone may selectively be varied through a large range of values to obtain the desired absorption characteristics.

The objects and features of the present invention will be best understood from the following description of the accompanying drawings, in which:

FIGURE 1 is a perspective view, partially broken away, illustrating a first embodiment of an absorber array constructed in accordance with the invention utilizing horns having circular mouths;

FIGURE 2 is a perspective view showing a portion of a horn array comprising horns having rectangular mouths and circular throats;

FIGURE 3 is a cross sectional elevation view of a portion of a sound absorber array incorporating a first modification of the embodiment of FIGURE 1;

FIGURE 4 is a cross sectional elevation view of a second embodiment of the invention;

FIGURE 5 is a perspective view, partially in section, illustrating a single dual-range absorber cell, constructed in accordance with the invention; and

FIGURE 6 is an equivalent circuit diagram useful in the exposition of the invention.

There is shown in FIGURE 1 a perspective view, partially broken away, illus-

trating the construction of a first embodiment of the invention. This sound absorber device comprises an impermeable backing sheet 1, which may be fabricated from metal, plastic, ceramic, or other suitable material, and an "egg-crate" core which abuts backing sheet 1. This core comprises a plurality of orthogonally intersecting partitions such as indicated at 2 and 3. The partitions (2-3) are normal to the surface of backing sheet 1 and preferably secured thereto by bonding or other suitable means. The partitions (2-3) define a plurality of cavities, cells, or compartments, having a specified interior volume. An array of horns nests within the cellular or compartmented core. This array 4 preferably comprises an integral structure which may be fabricated from plastic, metal, or other suitable material. Typically, the array 4 is fabricated from vacuum-formed plastic. The array comprises a plurality of short horns, a typical one of which is shown partially cut away at 5. The throat 6 of the horn 5 is open and communicates with the interior of the compartment bounded by partitions 2 and 3. The remaining two vertical partitions comprising the compartment are omitted in FIGURE 1 for purposes of illustration only, it being understood that a fully enclosed compartment is required for proper operation of the device. The axial length of the horn 5 is shorter than the depth of the compartment (2-3) thereby allowing the throat passage to communicate with the interior of the compartment. The mouth 7 of the horn 5 is circular and is flared towards the planar portion 8 of the array. Compartment 9 is substantially identical to the previously defined compartment and, as in the first instance, is shown with an open side in FIGURE 1 for purposes of clarity, it being understood that in practice all of the compartments or cells are bounded on five sides by planar walls or partitions and bounded on the sixth side by the horn array 4.

Overlying the array 4 is a permeable facing sheet 11, which may be fabricated from fiber metal, perforated metal, porous paper, porous ceramic, or other suitable permeable material having a specified flow resistance as defined hereinafter. It is preferred that the entire assembly, namely the backing sheet 1, the cellular core 2-3, the array 4 and the facing sheet 11 are bonded together by an adhesive or other suitable means.

The cut-off frequency of the horns (e.g., horn 5) comprising the array is determined by their shape. The design of the horn follows classical horn design criteria, well known to those versed in the art. As is also well known to those versed in the art,

the shape is determined in part by the flare rate. Any of a number of common horn shapes may be used, as desired, including exponential, hyperbolic, catenoidal, Bessel, and conical shapes. While the number of possible horn shapes is very large, for purposes of simplicity it is assumed that all of the horns, except those of FIGURE 2, have axial symmetry. This is not, as will be seen in FIGURE 2, an inherent limitation of the invention.

The mouths of the horns shown in array 4 of FIGURE 1 are circular. However, the array may be designed to utilize horns having rectangular or square mouths such as shown in the array 12 of FIGURE 2. Other horn geometrics may be selected, as desired. In any event, above the cut-off frequency, each horn of the array can transmit or propagate sound waves freely. Below the cutoff frequency, the air particles in the entire horn move together and exhibit, thereby a considerable inertia. In this respect, it is convenient to think of the air mass within each horn as being a "slug" of air which moves as a single unit below the cut-off frequency. At some frequency below cut-off the inertia of this slug (of air) in the horn is just compensated by the stiffness of the air confined within the cell, and a Helmholtz resonance occurs. The resonant frequency is largely determined by the volume of the cavity, in accordance with classical theory. This resonance is made to be heavily damped by the presence of the permeable facing sheet 11 extending across the mouth 7 of the horn 5.

Above the cut-off frequency, the horn 5 propagates incoming acoustic waves in the normal operating mode of a horn, but the discontinuity in area at the junction of the throat 6 and the air within the cell causes an acoustical reflection to occur. That is, sound propagated from the mouth toward the throat will be reflected and propagated from the far end of the throat back toward the mouth. Thus, above the cut-off frequency, the system behaves much in the manner of a conventional laminar absorber wherein destructive interference occurs between incoming and reflected sound waves.

By proper selection of the horn parameters, the volume of the cavity, and the resistance of the facing, the low-frequency absorption portion of the spectrum and the high-frequency absorption portion of the spectrum may selectively be varied through a wide range of values. Preferably these values are made to complement the spectrum of the noise to be absorbed, and thereby maximize the performance of the device.

There is shown in FIGURE 3 a cross-sectional elevation view of a modified form

of the apparatus of FIGURES 1 and 2. In this embodiment, the throat of the horn is made to extend all of the way to the bottom of the receiving cell and a window is provided in a side wall of the end of the throat for communication with the interior volume of the cell. This configuration comprises a permeable facing sheet 14 and an interposed cellular core comprising a plurality of wall members 15 and 16, and a horn 17 which extends from the top of the array to the bottom of the core (15-16). The mouth 18 of the horn 17 abuts permeable facing sheet 14 and is bounded by the upper end of the cell defined by wall members 15 and 16. The throat end 19 of horn 17 abuts backing sheet 13 and is centrally disposed within the wall members 15 and 16. Since it is necessary for the interior of the horn 17 to communicate with the air mass in the interior of cell 21, a sidewall window or aperture 22 is provided at the throat end 19 of horn 17. The adjacent cell 20 is similarly provided with a horn 23 having an aperture 24 at its throat end. The entire array comprises a plurality of like horns nested within like receiving cells comprising the core, of the type just described.

The advantage of the embodiment shown in FIGURE 3, as contrasted with the constructions shown in FIGURES 1 and 2, is that the structural strength of the assembly is improved by the central connection of the depending end (viz., the throat end 19) of the horn with the backing sheet 13. The acoustical performance of the embodiment of FIGURE 3 is substantially the same as that provided by the first described embodiments.

In certain instances it is desirable to broaden or smooth out the operating characteristics of the apparatus. This can be achieved by modifying the apparatus of FIGURE 3 in the manner shown in FIGURE 4. The apparatus of FIGURE 4 is generally similar to that shown in FIGURE 3 in that it comprises an impermeable backing sheet 25, permeable facing sheet 26, and a plurality of closed cells bounded by wall members 27, 28 and 29. A plurality of horns 31, 32 are disposed within corresponding cells 33 and 34. The height of wall member 28 is shorter than that of wall members 27 and 29, and is equal to the length of horns 31 and 32. It is to be noted, however, that the axial length of horns 31, 32 is less than the height of wall members 27 and 29, thus allowing a space to exist between the mouths 35 and 36, respectively, of horns 31 and 32, and the facing sheet 26. This intervening space between the facing sheet 26 and the horn array permits both horns (31-32) to share the greater area of ex-

posed facing sheet 26.

Horn 31 is constructed in essentially the same manner as that of horn 17 described in connection with FIGURE 3. However, horn 32 differs from horn 31 in that the sidewall aperture 37 is located intermediate the throat 38 and the mouth 36 of the horn, rather than at the throat end (38) of the horn, as in the case of horn 31. By locating the aperture 37 some distance from the throat end, the resonant frequency of the horn-cavity combination will be shifted to a higher frequency than would otherwise be the case. Thus, the absorption characteristics will differ from that of the adjacent horn-cavity assembly 31, 33. Inasmuch as permeable facing sheet 26 spans the mouths of both horns 31 and 32, and is operatively shared by them, the absorption response characteristics of the horn pair will be broadened.

The placement of the aperture 37, in effect "tunes" the resonant frequency of the device much in the same manner that horn-type musical instruments are tuned by means of openings spaced along the length of the horn. In a typical construction, horn 31/cavity 33 combination would be designed to absorb the lowest frequency of interest and horn 32/cavity 34 combination would be tuned to that higher frequency at which the first cell became relatively ineffective. For example, horn 31/cavity 33, functioning as a damped resonator, would absorb the lowest frequency portion of the spectrum, horn 32/cavity 34, functioning as a damped resonator, would absorb the next higher portion of the spectrum, horn 31/cavity 33, functioning as a laminar absorber, would absorb the next higher portion of the spectrum, and horn 32/cavity 34, functioning as a laminar absorber, would absorb the highest portion of the spectrum. Thus, the paired absorber horn/cell combinations would have an efficient absorption band extending over an unusually wide range. A design dividing the spectrum into four zones is meant to be exemplary only, it being understood that the absorption characteristic curve may be modified as desired by the designer.

It should be understood that the lowest frequency absorption peak lies considerably below the design cut-off frequency of the horn. Also, the next higher frequency absorption peak will be approximately a factor of ten above the fundamental absorption frequency. There will follow a series of successively higher frequency absorption peaks spaced at approximately one-half wavelength intervals. Thus, the overall absorption bandwidth will be unusually wide.

There is shown in FIGURE 5 a single sound absorber cell constructed in accord-

ance with the invention. For very low frequencies it may be desirable to construct appropriately large sound absorbers which would be used independently as contrasted with the multiple-absorber, or array configuration, as previously described. Such a unitary construction is shown in FIGURE 5 and comprises a cylindrical cavity-defining enclosure 39 constructed of metal or other impermeable material. Cavity defining enclosure 39 is bounded on its upper end by a permeable disc 41 which functions as the flow-resistive facing sheet for horn 42. The axial length of horn 42 is such as to permit a space 43 to exist between the interior surface of end-closing wall 44 and the throat end of horn 42. This allows the air within horn 42 to communicate with the air within cavity defining enclosure 39. In a typical construction of the invention designed to have its lowest absorption (i.e., fundamental frequency) at 60 Hz and its next higher frequency absorption peak at approximately 600 Hz, the device would have an axial depth 45 of approximately nine inches and an interior diameter 46 of approximately eight inches. Horn 42 would have a flare rate designed to cut-off at approximately 400-500 Hz. The flow resistance of permeable facing disc 41 would be of the order of  $1 \rho c$  (42 rays) where  $\rho$  is the density of the fluid medium through which the sound is propagated and  $c$  is the velocity of sound in said medium.

For convenience of manufacture, facing disc 41 may be recessed within cavity defining member 39 so as to present a flush surface.

There is shown in FIGURE 6 a schematic diagram of a network which is the electrical analogy of the apparatus of FIGURES 3 and 4. As can be seen, the network comprises a first resistance  $R_1$  and series inductance  $L_1$  which correspond to the lumped acoustical impedance of the permeable facing sheet. This impedance is in series with an impedance  $Z_1$  which corresponds to the impedance looking into the mouth of the horn. The adjacent sound absorption cell likewise comprises a resistance  $R_2$  and a series inductance  $L_2$  corresponding to the impedance of the flow resistive sheet. Both  $R_2$  and  $L_2$  are in series with impedance  $Z_2$ , which corresponds to the input impedance of the corresponding horn mouth. In the embodiment of the apparatus shown in FIGURE 3, there is no leakage between adjacent absorber cells. However, in the embodiment of FIGURE 4 the open space between the mouths of adjacent horns and the common, permeable, facing sheet, results in a leakage resistance which is shown in the equivalent circuit as shunt resistance  $R_3$ . In the em-

bodiment of FIGURE 3, the shunt resistance  $R_3$  would be infinite, and in the embodiment of FIGURE 4 it may be made to approach zero (e.g., a short circuit). The value of the shunt resistance  $R_3$  is a design parameter which the acoustical engineer may adjust to meet individual application requirements. The convenience of equivalent-network analysis permits the designer to customize the sound absorber apparatus of the invention to meet predetermined performance objectives.

In the particular exemplary embodiments described, the resistance terms  $R_1$  and  $R_2$  have been provided principally by the flow resistance of a facing sheet extending over the mouth of the horns. However, it should be understood that in certain instances the facing sheet may be omitted, in which case the acoustical resistance inherent in the throat of the horn will be sufficient to provide the desired function. This arrangement is particularly suitable for applications of the invention intended for use at higher frequencies, in which the physical size of the horns is made relatively small and the intrinsic throat resistance is significant.

In the foregoing descriptions of the various embodiments of the invention, it has been stated generally that the apparatus comprises a horn which acoustically terminates in a Helmholtz resonator. It should be understood that the walls of the horn itself comprise a portion of the boundary of the resonator itself. That is, the interior volume of the Helmholtz resonator is, in part, constrained by the surface area of the nested horn, and must be reckoned in the design of the resonator chamber.

In summary, there has been shown and described a dual-range apparatus for the absorption of ambient-sound which functions in the low-frequency end of the acoustic spectrum as a heavily damped Helmholtz resonator. At higher regions of the acoustic spectrum, the same apparatus functions effectively as a laminar absorber in which the reflection caused by the discontinuity, or change in area, between the throat of the horn and the interior of the resonant chamber will cause a series of absorptive peaks to occur in the system's response. By combining two such absorber devices in parallel, one of which is made to complement the absorptive peaks of the other, a relatively smooth, wide-range, absorption characteristic may be obtained. Thus, there is provided an unusually compact device having the capability of absorbing ambient sounds over a wider range than possible by prior devices of comparable physical volume, and particularly with respect to the lowest effective absorption frequency.

## WHAT WE CLAIM IS:—

1. Apparatus for the absorption of a wide frequency range ambient sound field, comprising means defining a sound-confining chamber and, an acoustical horn having a predetermined cut-off frequency and having a sound-receiving mouth at one end and a smaller throat at the other end of the horn path, said path being characterized by a continuously changing cross-sectional area along its length, said horn being nested within said chamber so as to have said mouth acoustically coupled to the exterior of said chamber and said throat acoustically coupled to the interior of said chamber, the internal volume defined by said chamber and said horn comprising a damped Helmholtz resonator, whereby incoming sound above said cut-off frequency will be propagated from said mouth towards said throat whereupon said sound will be reflected back toward said mouth due to the discontinuity at the junction of said throat and said chamber, thereby causing destructive interference between incoming and reflected sound waves, and whereby the inertia of the air mass in said horn resulting from incoming sound below said cut-off frequency is just compensated by the air confined in said chamber so as to cause Helmholtz resonance to occur within said chamber.
2. Apparatus as defined in claim 1, including a permeable flow-resistive element placed in series, acoustically, with said mouth and the ambient sound field, the flow resistance of said element being sufficient to heavily damp the resonance of said chamber at frequencies below said cut-off frequency.
3. Apparatus as defined in claim 2, wherein said flow-resistive element extends across the mouth of said horn.
4. Apparatus as defined in claim 2 or 3, wherein said flow-resistive element has a flow resistance of the order of  $1 \rho c$  where  $\rho$  is the density of the fluid medium through which the sound is propagated and  $c$  is the velocity of sound in said medium.
5. Apparatus as defined in any of the preceding claims, wherein said chamber defining means comprises a cylinder closed at one end by a sound confining end wall and closed at the other end by the mouth of said acoustical horn.
6. Apparatus as defined in any of the preceding claims, wherein said throat of said horn is acoustically coupled to the interior of said chamber via an aperture in the side wall of said horn.
7. Apparatus as defined in any of the preceding claims, wherein said horn has a continuous exponential taper and said

mouth thereof is contiguous with the outer surface of said chamber

8. A wide-frequency range sound absorber, comprising a parallel array of tuned Helmholtz resonator compartments and, a plurality of acoustical horns each having a predetermined cut-off frequency and a sound-receiving mouth at one end and a smaller open throat at the other end of the horn path, each of said horns being nested within corresponding compartments so as to have the mouths thereof acoustically coupled to the exterior of said array and the throats thereof acoustically coupled to the interior of corresponding compartments, said horns being characterized by a continuously-diminishing cross-sectional area between said mouths and said throats, whereby incoming sound above said cut-off frequency will be propagated from said mouths towards said throats whereupon said sound will be reflected back toward said mouths due to the discontinuity of the junctions of said throats and said compartments, thereby causing destructive interference between incoming and reflected sound waves, and whereby the inertia of the air masses in said horns, resulting from incoming sound below said cut-off frequency, is just compensated by the air confined in said compartments so as to cause Helmholtz resonance to occur within said compartments.

9. A wide-frequency range sound absorber as defined in claim 8, including permeable flow resistance means placed in series, acoustically, with said mouths and the ambient sound field to be absorbed.

10. A wide-frequency range sound absorber comprising first and second sound-confining resonator compartments disposed in side-by-side relationship, said compartments having adjacent open ends, a first acoustical horn having a sound-receiving mouth at one end and a smaller open throat at the other end of the horn path, said path being characterized by a continuously changing cross-sectional area along its length, said horn being nested within said first compartment and having its throat in communication with the interior thereof, a second acoustical horn nested within said second compartment and having its throat in communication with the interior thereof, the cut-off frequency of said first horn being dissimilar to the cut-off frequency of said second horn and, a permeable flow-resistive element extending across the mouths of said first and second horns whereby the combination of said first horn and said first compartment is responsive to absorb a first distributed portion of the sound spectrum and the combination of said second horn and said second compartment is responsive to ab-

sorb a complementary distributed portion of the sound spectrum.

11. A wide-frequency range sound absorber constructed and adapted to operate substantially as herein described with reference to the accompanying drawings.

LANGNER PARRY  
Chartered Patent Agents  
Chichester House  
278-282 High Holborn  
London, W.C.1  
Agents for the Applicants

Printed for Her Majesty's Stationery Office by The Tweeddale Press Ltd., Berwick-upon-Tweed, 1977.  
Published at the Patent Office, 25 Southampton Buildings, London, WC2A 1AY, from which copies may be obtained.

## COMPLETE SPECIFICATION

**This drawing is a reproduction of the Original on a reduced scale.**

**SHEET 1**

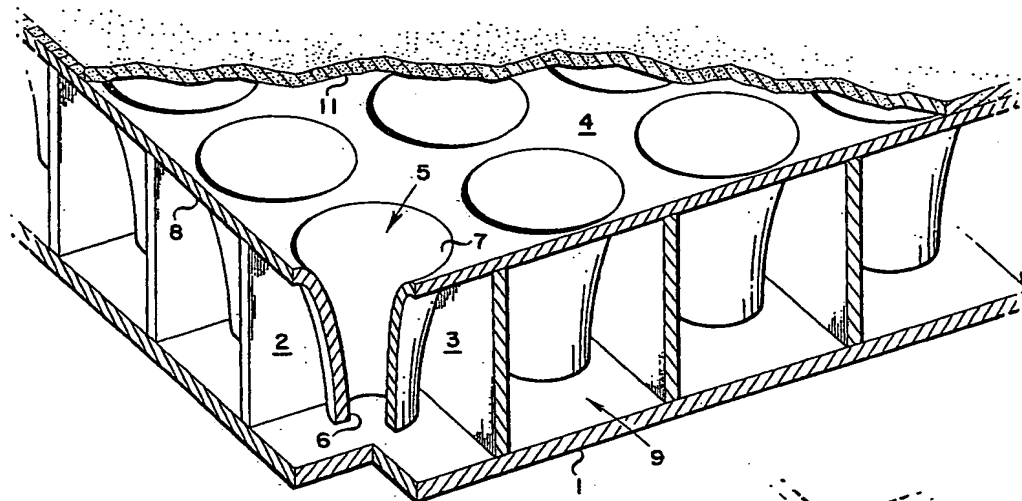


FIG. 1

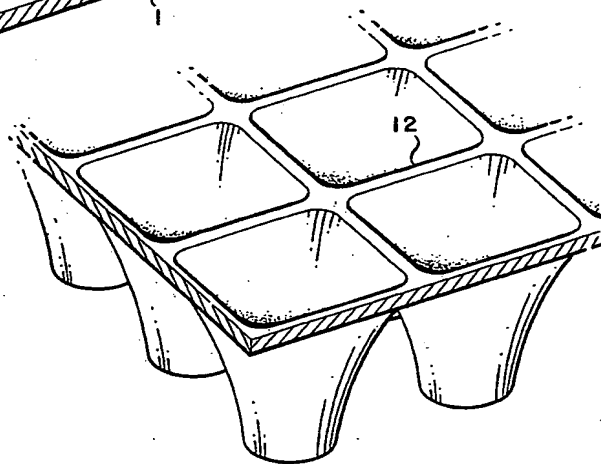


FIG. 2



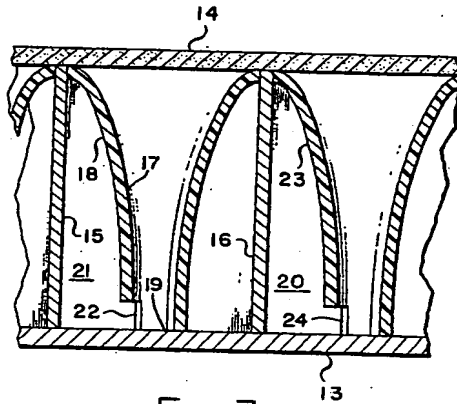


FIG. 3

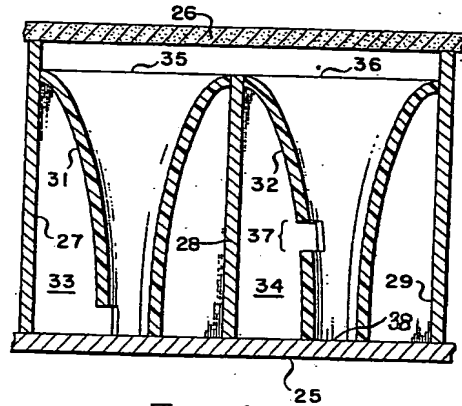


FIG. 4

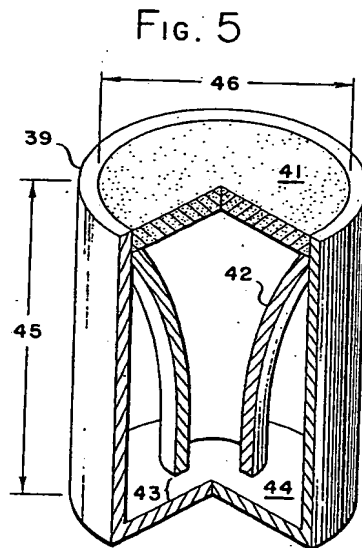


FIG. 5

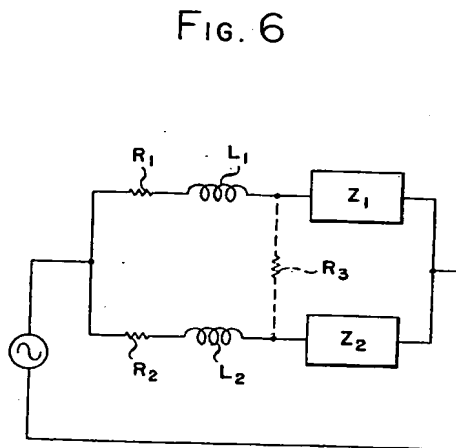


FIG. 6